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Modeling and field evidence of finger formation and finger recurrence in a water repellent sandy soil

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Abstract. With prolonged rainfall, infiltrating wetting fronts in water repellent soils may become unstable, leading to the formation of high-velocity flow paths, the so-called fingers. Finger formation is generally regarded as a potential cause for the rapid transport of water and contaminants through the unsaturated zone of soils. For the first time, field evidence of the process of finger formation and finger recurrence is given for a water repellent sandy soil. Theoretical analysis and model simulations indicate that finger formation results from hysteresis in the water retention function, and the character of the formation depends on the shape of the main wetting and main drainage branches of that function. Once fingers are established, hysteresis causes fingers to recur along the same pathways during following rain events. Leaching of hydrophobic substances from these fingered pathways makes the soil within the pathways more wettable than the surrounding soil. Thus, in the long-term, instability-driven fingers might become heterogeneity-driven fingers.

1. Introduction

In the unsaturated zone, water and solutes often move preferentially through paths that are usually wetter and carry more water per unit area than the surrounding dry soil [*Gee et al*., 1991; *Jury and Flühler*, 1992]. These preferential flow paths, or fingers, can be heterogeneity- or instability-driven. Heterogeneity-driven fingers generally occur in clay and peat soils with well-defined macropore or mesopore networks [*Beven and Germann*, 1982; *White*, 1985; *Bronswijk et al*., 1995], while instability-driven fingers can be found in water repellent soils [*Hendrickx et al*., 1993; *Ritsema et al*., 1993; *Ritsema and Dekker*, 1994, 1996b] and coarse-grained soils [*Glass et al*., 1989a, b; *Liu et al*., 1993, 1994a]. This paper deals with water repellent soils.

Water repellency is a plant-induced soil property [*Roberts and Carbon*, 1972; *Ma'shum et al*., 1988; *Wallis and Horne*, 1992; *Bisdom et al*., 1993]. Decay of organic compounds produces substances such as humic and fulvic acids, which coat the soil surfaces and make the soil water repellent [*Wander*, 1949; *Van 't Woudt*, 1959; *McGhie and Posner*, 1980; *Giovannini et al*., 1983; *Dekker and Ritsema*, 1996b]. Because organic matter resides in the upper soil layers, water repellency is restricted to this zone [*Wallis and Horne*, 1992; *Dekker and Ritsema*, 1996a]. Water repellent soils occur in many parts of the world, in all types of climates [*Krammes and DeBano*, 1965; *DeBano*, 1969; *McGhie*, 1987; *Dekker and Jungerius*, 1990], and can be found beneath different vegetation types, including forests, brushwood, heath, grassland, arable land, and golf courses [*DeBano*, 1981; *Wallis and Horne*, 1992]. The degree of water repellency depends on the vegetation type. Extremely water repellent soils can be found beneath grass, regardless of the type of soil [*Dekker and Ritsema*, 1996a].

Water repellency is most pronounced in dry soils. It does not occur in wet soils [*DeBano*, 1971; *King*, 1981; *Wallis et al*., 1990; *Dekker and Ritsema*, 1994; *Ritsema and Dekker*, 1994], because the high moisture content induces molecular conformational changes in the organic substances responsible for water repellency [*Ma'shum and Farmer*, 1985; *Wallis et al*., 1990]. Water infiltration in initially dry, water repellent soils is retarded compared with infiltration in wet soils [*Wallis et al*., 1991], causing water to be retained in the top layer at first. With prolonged rainfall, minor perturbations in an originally planar infiltrating wetting front may grow to form fingers. Although rapid transport through fingers in water repellent soils has been reported recently [*Van Dam et al*., 1990; *Hendrickx et al*., 1993; *Ritsema et al*., 1993; *Ritsema and Dekker*, 1995], the mechanisms of finger formation and finger recurrence have been unclear.

The objectives of the present study are (1) to present field evidence of the process of finger formation and finger recurrence in a water repellent sandy soil, and to explain the process of formation and recurrence; (2) to simulate finger formation and finger recurrence using a numerical solution of coupled water and air flow in a two-dimensional domain; and (3) to propose a hypothesis for the effect of finger recurrence on formation of heterogeneity in soil water retention properties.

2. Mechanism for Finger Formation and Recurrence

Fingered flow of water in soils is induced by the instability of the wetting front of the infiltrating water [*Glass et al*., 1989a, b;

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Selker et al., 1992]. Unstable conditions prevail for infiltrating water when the pressure gradient for the water phase is opposite (upward) to the direction of flow (downward). *Raats* [1973] explained that unstable flow can occur for hydrophobic soils, for soils with steep wetting retention curves, or when air pressure increases significantly above ambient atmospheric pressure ahead of the wetting front. A necessary condition for unstable flow is that the water application rate be less than the saturated hydraulic conductivity of the receiving soil.

The mechanism for the initial formation of the fingered flow pathways and their subsequent recurrence can be described in terms of the water retention and hydraulic conductivity properties of the soil [*Glass et al.*, 1989b; *Liu et al.*, 1994a]. The details of such a description have been given by *Nieber* [1996]. In this description Nieber explained that the water entry capillary pressure, h_{mwe}, on the main wetting water retention curve and the air-entry capillary pressure, h_{mae}, on the main drainage water retention curve are critical parameters to assess the formation of fingered flow in initially dry porous media. He hypothesized that if $h_{mwe} < h_{mae}$, then finger formation will occur, and subsequent wetting events will produce finger recurrence. Using a numerical solution of Richards' equation, he demonstrated this hypothesis to be valid.

3. Mathematical Description of Fingered Flow

The mass balance equations for coupled two-dimensional flow of water and air in an unsaturated soil are expressed as

$$\frac{\partial M_w}{\partial t} = \frac{\partial}{\partial x}\left(\rho_w K_w \frac{\partial h_w}{\partial x}\right) + \frac{\partial}{\partial z}\left(\rho_w K_w \frac{\partial h_w}{\partial z}\right) + \frac{\partial(\rho_w K_w)}{\partial z} \qquad (1)$$

$$\frac{\partial M_a}{\partial t} = \frac{\partial}{\partial x}\left(\rho_a K_a \frac{\partial h_a}{\partial x}\right) + \frac{\partial}{\partial z}\left(\rho_a K_a \frac{\partial h_a}{\partial z}\right) \qquad (2)$$

where

$M_w = \Phi\rho_w S_w$ mass of the water phase per unit volume of the porous medium [kg/m^3];
$M_a = \Phi\rho_a S_a$ mass of the air phase per unit volume of the porous medium [kg/m^3];
Φ porosity of the porous medium [1];
S_w, S_a degree of saturation for the water and air phases, respectively [1];
h_w, h_a pressure heads for the water and air phases, respectively [m];
K_w, K_a hydraulic conductivities for the water and air phases, respectively [m/min];
ρ_w, ρ_a densities for the water and air phases, respectively [kg/m^3];
x, z cartesian coordinates [m];
t time [min].

Note that both fluid compressibility and porous medium compressibility are included implicitly in these equations.

These equations are augmented by the relations

$$h = h_a - h_w$$

$$\rho_w = \rho_w(h_w), \quad \rho_a = \rho_a(h_a), \quad \Phi = \Phi(h_w, h_a)$$

$$\theta_w = (\theta_{w_s} - \theta_j)\left(\frac{1}{1 + (\alpha_j h)^{n_j}}\right)^{1-(1/n_j)} + \theta_j \qquad j = md, mw$$

$$S_{w_e} = \frac{S_w - S_r}{1 - S_r} = \frac{\theta_w - \theta_r}{\theta_s - \theta_r}$$

$$S_a = 1 - S_w$$

$$K_w = K_{w_s} S_{w_e}^{1/2}[1 - (1 - S_{w_e}^{n_j/n_j-1})^{1-(1/n_j)}]^2, \; S_{w_e} > 0 \quad j = md, mw$$

$$K_w = 0, \qquad S_{w_e} \le 0$$

$$K_a = K_{a_s}(1 - S_{w_e})^{1/2}[1 - S_{w_e}^{n_j/(n_j-1)}]^{2-(2/n_j)} \qquad j = md, mw$$

where h is the capillary pressure [m]; K_{w_s} and K_{a_s} are the saturated hydraulic conductivities for the water and the air phases, respectively [m/min]; S_{w_e} is the effective saturation of the water phase [1]; θ_w is the volumetric water content [m^3/m^3]; θ_{w_s} is the saturated volumetric water content [m^3/m^3]; θ_r ($= \theta_{md}$) is the residual water content on the main drainage function [m^3/m^3]; θ_{mw} is the air-dry water content on the main wetting function [m^3/m^3]; and α_j [m^{-1}] and n_j [1] are porous media dependent parameters for the main wetting function ($j = mw$) and for the main drainage function ($j = md$). Note that although the fluid retention and hydraulic conductivity relations proposed by *van Genuchten* [1980] were used in the above descriptions, alternative empirical formulae could be used as well.

The hydraulic conductivity equations for water given above are consistent with the notion that the water phase hydraulic conductivity will be zero when the water content is below the residual water content. The fact that the water phase hydraulic conductivity is zero at the wetting front of an initially air-dry porous medium has been shown experimentally by *Lu et al.* [1994] using photomicroscopic imaging of glass bead media. They showed that the wetting front moved by erratic advances into the initially air-dry media.

As described in the last section, the process of capillary hysteresis is important in the formation of fingers and their recurrence. To describe capillary hysteresis, a number of alternative models could be applied. In this paper we apply the independent domain model of *Mualem* [1974].

The numerical solution of the two-phase flow problem is achieved using the finite element method with bilinear finite elements and a fully implicit time-discretization scheme. The modified-Picard procedure for the two-phase flow equations, as described by *Celia and Binning* [1992], is applied to solve the nonlinear step of the solution process. In addition, the nodal hydraulic conductivity weighting scheme introduced by *Dalen* [1979] and described by *Huyakorn and Pinder* [1978] is used. The formulation of the numerical solution for the two-phase flow equations is similar to that presented by *Nieber* [1996] for the Richards equation, but in addition we account for medium and fluid compressibility and for the dynamics of the air phase.

To properly model the formation of fingers and their recurrence, it is essential that the associated sharp gradients in moisture content be maintained. This requirement is difficult to meet since most numerical schemes will produce some dissipation of sharp moisture fronts. *Nieber* [1996] showed that when hydraulic conductivities for water are upstream weighted, this can lead to artificial dissipation of an initial perturbation or of a forming finger. However, he demonstrated that if the nodal hydraulic conductivities are downstream weighted, then the sharp front can be maintained. The rules for assigning the hydraulic conductivity weighting factor are summarized by Nieber. In that study, these rules were applied only to the water phase, but they can also be applied to the air phase hydraulic conductivities as well.

The finite element solution was implemented in FOR-

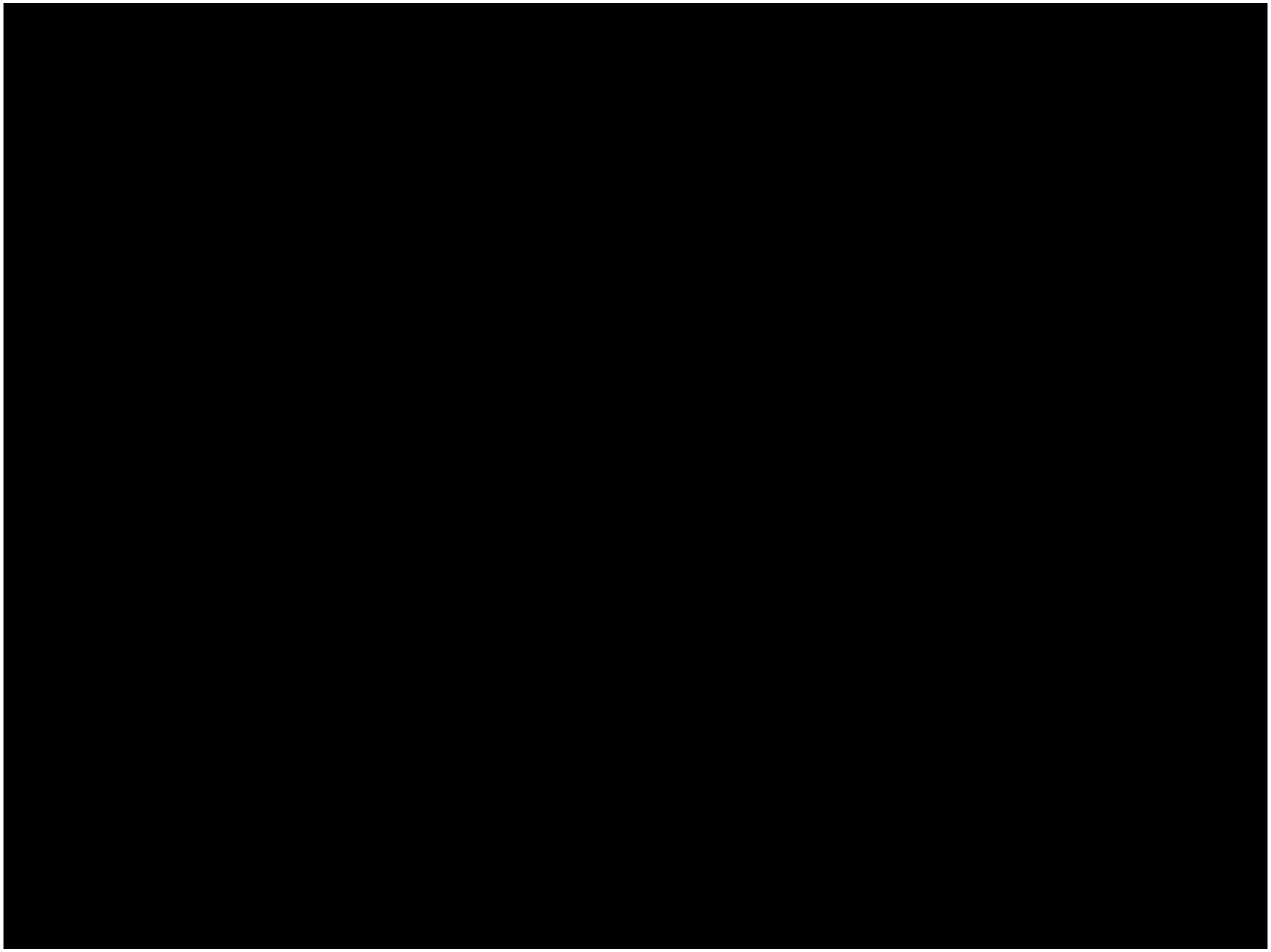

Plate 1. Soil water content changes in a transect in the sandy soil of Ouddorp during three rainy periods in December 1994 and January 1995, with 24 mm (December 7–9), 37 mm (December 26–27), and 17 mm of rain (January 7–10), respectively. The measurements reveal that fingers recurred at the same locations during each of these rain events.

TRAN-77 language on an SGI-ONYX computer. The numerical solution uses a diagonally preconditioned conjugate gradient method [*Pini and Gambolati*, 1990] to solve the matrix equations. Automatic time step adjustment of the solution and determination of nonlinear solution convergence were achieved with the procedures described by *Kaluarachchi and Parker* [1989]. For this paper the relative and absolute errors in fluid pressure head were set to 0.0001 and 0.0001 m, respectively. An additional criterion for determination of nonlinear solution convergence was the testing of the change in fluid saturation, with the maximum allowable change between iterations set to 0.0001.

As mentioned previously, the process of capillary hysteresis was modeled using the independent domain model of *Mualem* [1974]. In the implementation of this model the capillary pressure at each node point is checked at the end of solution convergence to assess whether a change in water retention function is warranted.

4. Materials and Methods

4.1. Experimental Site

The field experiments were conducted at a water repellent sandy field site near Ouddorp in the southwestern part of the Netherlands. The grass-covered soil consisted of a 9-cm-thick humus surface layer on top of a fine dune sand having a thickness of up to 200 cm. The soil was classified as a mesic Typic Psammaquent [*De Bakker*, 1979]. The organic matter content of the topsoil was around 20%, and below 9 cm depth it was less than 0.5%. The median dimension of the dune sand fraction was 170 μm. Annually, groundwater fluctuated between 60 and 200 cm below the soil surface.

4.2. TDR Measurements

To obtain two-dimensional water content distributions in a vertical transect, use has been made of a fully automated, stand-alone Trase (system 1, Soilmoisture Equipment Corporation, Santa Barbara, California) TDR (time domain reflectometry) measurement device. The TDR device was connected to 98 20-cm-long, three-wire TDR probes, which were installed in a 195-cm-long and 70-cm-deep transect at depths of 4, 12, 20, 30, 40, 55, and 70 cm. At each depth, 14 TDR probes were installed horizontally in the soil at intervals of 15 cm. Measurement frequency was once every 3 hours. At the same site, rainfall and water table depth were recorded automatically. The soil water content data derived from these measurements are used to illustrate the formation and recurrence of fingers within the field soil.

4.3. Soil Block Sampling

To obtain three-dimensional images of water content and water repellency patterns, a 120-cm-long, 60-cm-wide, 52-cm-deep soil block was excavated in a systematic way using 1400 100-cm^3 (5 cm in diameter and 5 cm high) steel cylinders. Sampling started at the soil surface and continued downward. Seven soil layers were sampled, at depths of 0–5, 7–12, 14.5–19.5, 22–27, 29.5–34.5, 37–42, and 47–52 cm. At each depth, 200 samples were taken (10 by 20). The sampling grid was derived from and based upon experiences with two-dimensional sampling schemes formerly used in the same experimental field to detect preferential flow paths [*Ritsema and Dekker*, 1996a]. Each sample was used for the determination of the soil water content (oven drying at 65°C) and for determining the degree of water repellency by applying the water drop penetration time (WDPT) test. The degree of potential water repellency was measured on the oven-dried soil samples. After oven drying, the samples were stored for at least 2 days at 20°C and a relative air humidity of 50% before measurements were conducted. Three drops of distilled water from a standard medicine dropper (approximately 6 mm in diameter) were placed on the smoothed surface of a soil sample, and the time it took to penetrate into the soil was recorded. Ten classes were distinguished: wettable or non–water repellent soil (<5 s), and slightly (5–60 s), strongly (60–600 s), severely (600–3600 s) and extremely water repellent soil, with classes 1–2, 2–3, 3–4, 4–5, 5–6, and >6 h.

Three-dimensional visualizations of water content and water repellency distributions were made using the Iris Explorer (version 2.2) modular visualization software environment of Silicon Graphics, Incorporated (SGI). These visualizations are used to support a hypothesis regarding the formation of preferential flow paths due to the dissolution of hydrophobic substances along flow paths formed by instability-driven fingered flow.

5. Results

5.1. Field Observations of Finger Formation and Finger Recurrence

In situ soil water contents were measured in a 195-cm-long, 70-cm-deep transect using TDR. In Plate 1, the moisture contours show the appearance and disappearance of fingers during three different rain events in the period from December 1994 to January 1995. Plate 1 clearly reveals that the fingers always formed at the same locations during the three rain events. On December 7, most of the soil was dry, with the exception of the humic topsoil, which had a volumetric water content between 10% and 25%. Between December 7 and 10, 24 mm of rain fell, most of it concentrated in the night of December 8 and the early morning of December 9. Two distinct wet fingers were formed during this rainy period, the one to the left of the middle of the transect starting slightly earlier than the one to the right. No rain was registered during the second half of December 9. Because of drainage, soil water contents within the fingers were much lower on December 9 (10:30 P.M.) than those observed during the rainfall event.

In the period that followed, the soil dried out, and on December 26, shortly before the next rain (37 mm), the soil water content distribution was found to be more or less the same as that on December 7. Widths and locations of the fingers on December 27 and 28 were the same as those during the earlier storm, as can be seen by comparing, in Plate 1, the wetting patterns for December 8 (4:30 P.M.) and December 27 (4:30 A.M.), as well as those for December 9 (4:30 A.M.) and December 27 (10:30 A.M.). Owing to the copious rainfall on December 27 and 28, fingers protruded through the entire subsoil, causing the profile to become wetter than had been observed on December 7–9.

Rainfall did not occur between December 27, 1994, and January 7, 1995, and the soil profile dried out again. The 17-mm rainfall that followed resulted in finger patterns similar to those on the two earlier dates. How far fingers actually protrude through the sandy subsoil mainly depends on the wetting history of the soil and on the rainfall characteristics. The soil water content measurements during the three rain events clearly demonstrated that fingers recurred at the same locations and that fingers were formed during the course of single rain events, indicating their possible accelerating effect on downward water movement and solute transport.

5.2. Numerical Simulation of Finger Formation and Finger Recurrence

The purpose of the numerical simulations to follow is to demonstrate the process of finger formation and recurrence. It is not our objective to match field conditions exactly, so the simulated flow domain was not chosen to be identical to the flow domain observed at the Ouddorp site. However, it is worthwhile to note that the simulation of the observed field data is the subject of an ongoing study.

To illustrate the process of finger formation and recurrence, we consider a vertical flow domain 0.5 m high and 0.2 m wide. The top boundary has a boundary condition of specified water flux and specified air pressure of zero. During water applications the application rate is 1/6 of the saturated water hydraulic conductivity of the soil. The bottom boundary is a seepage boundary for water. Air pressure is specified to be zero along the bottom boundary until it becomes saturated with water, at which time a condition of zero air flux is specified. The vertical boundaries are assumed to be impermeable to both water and air. Initially the entire region is air-dry, except for a small saturated region at the top with a perturbed front. This saturated region corresponds to the wetted domain which exists just prior to the destabilization of the wetting front. The perturbed front corresponds to the destabilization process. Alternatively, the perturbed front could also correspond to a larger-scale perturbation caused by a wavy interface between textural horizons, as observed at the Ouddorp site. For the cases shown here the perturbed front was generated using a summation of 20 sine waves of equal amplitude and frequency but of randomly generated phase. For the finite element solution the flow domain was discretized using a node spacing of 0.005 m in each coordinate direction.

Two porous media are treated in the numerical simulations. One of the porous media, referred to as porous medium A, has properties that will promote finger growth and recurrence, while the other, porous medium B, will tend to dissipate any initial perturbations or finger formation. The common parameters for the two porous media are given as

$$\Phi = \text{const} = \theta_s = 0.35$$

$$\theta_r = 0.05, \qquad K_{w_s} = 0.1 \text{ m/min}$$

$$K_{a_s} = 6.0 \text{ m/min}$$

$$\theta_{mw} = 0.005$$

$$\rho_w = 1000(1 + 4.3x10^{-6}h_w) \text{ kg/m}^3$$

$$\rho_a = 1.24(1 + 0.1h_a) \text{ kg/m}^3$$

Note that a linear function is applied for the variation of water density [*Freeze*, 1971] and air density [*Celia and Binning*, 1992] with respect to the corresponding fluid pressure. Also, the porous medium is treated as incompressible (Φ = const).

The difference between the two porous media are manifested in the main wetting and main drainage retention functions. The parameters for these functions for porous medium A are

$$\alpha_{mw} = 50.0 \text{ m}^{-1}, \qquad n_{mw} = 20.0$$

$$\alpha_{md} = 7.0 \text{ m}^{-1}, \qquad n_{md} = 10.0$$

while those for porous medium B are

$$\alpha_{mw} = 15.0 \text{ m}^{-1}, \qquad n_{mw} = 3.0$$

$$\alpha_{md} = 5.0 \text{ m}^{-1}, \qquad n_{md} = 3.0$$

The growth and persistence of preferential fingered flow paths in porous medium A is illustrated in Plate 2, which shows a sequence of images representing the distribution of water content in a soil profile during an event in which water was applied for 30 min, then stopped for 90 min, and applied again for 30 min. The inset in the plate shows the main wetting and main drainage retention functions for the parameters associated with porous medium A. These curves have characteristics similar to those for the hydrophobic textural horizon at the Ouddorp site. For this case, $h_{mwe} < h_{mae}$, so it is expected that fingers will form in this soil, growing from perturbations in the wetting front. The flow patterns shown in the plate show that fingers form during the first water application period and are drained following the cessation of water application. Although large moisture gradients exist near the fingers, lateral moisture movement is prevented by the mechanism described by *Nieber* [1996]. When water is again applied, beginning at 120 min, it moves preferentially down the previously formed finger pathways.

Now we consider a soil for which fingered flow does not occur. The hysteretic water retention function is presented in Plate 3, with images of water content distributions over a period of water application lasting 35 min. The initial condition and the boundary conditions are identical to those for the first case, except that here we consider only 35 min of continuous water application. For this porous medium, $h_{mwe} > h_{mae}$, and therefore water behind the wetting front will readily imbibe into the surrounding dry soil. The simulated results show that this imbibition does occur and the initially perturbed wetting front in this porous medium stabilizes after a very short period of time. The simulation results shown in Plates 2 and 3 thus convincingly show that the shape of the wetting branches determines whether a finger or a stable wetting front is formed.

5.3. A Hypothesis for the Formation of Heterogeneity-Driven Fingers

As was described above, the fingered flow pathways persist once they have formed. Repeated wetting and drying of these pathways over a protracted period of time will probably lead to the leaching of hydrophobic substances from the pores along the fingered flow pathways. This leaching will change the water retention functions of the porous media lying along these pathways and make it more wettable than the surrounding hydrophobic media. Thus, as time progresses, it is more likely that these pathways will develop into permanent preferential flow pathways because of heterogeneity in wettability. To test this hypothesis, the spatial distributions of soil water content and water repellency obtained from the soil block sampling were analyzed for correlative patterns.

The isosurface volumetric soil water content of 8.5% has been visualized in Plate 4, together with intersecting horizontal and vertical cutting planes. The development is similar to that shown in Plate 1, in that the fingers start at the layer interface at a depth of around 9 cm. Volumetric soil water content in the humic topsoil ranged between 12% and 40%, while the underlying dune sand had values of 12% and more within the fingers,

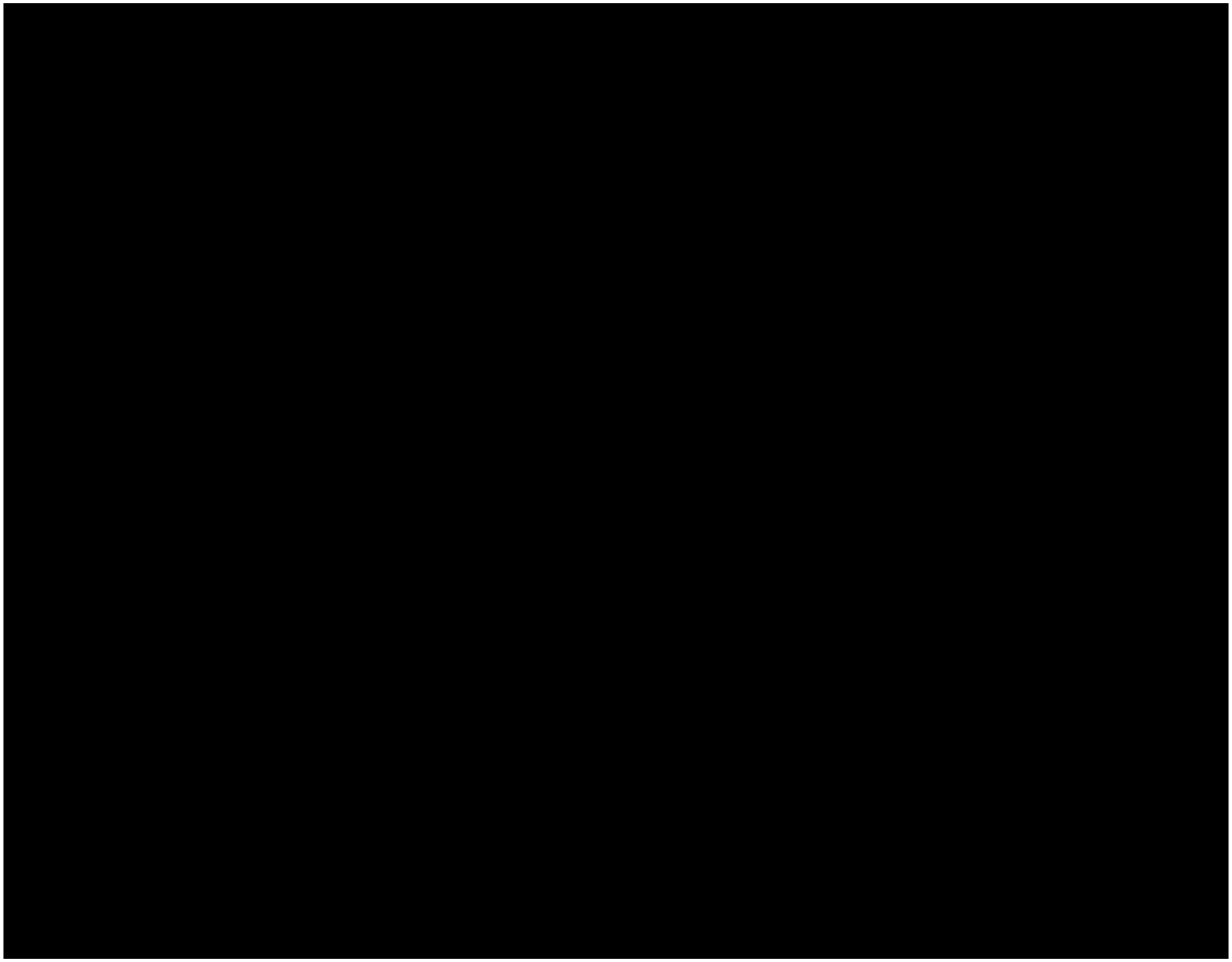

Plate 2. Illustration of fingered flow in a soil during the first wetting cycle, first drainage cycle and second wetting cycle. The fingers emanate from an initial perturbation in the wetting front at 0 min. The flow domain is 0.2 m wide and 0.5 m deep. The main wetting and main drainage branches of the water retention function for the soil are illustrated by the graphic insert. During wetting water is applied uniformly across the top of the flow domain at a rate of 1/6 of the saturated hydraulic conductivity of the soil. Water is applied for the first 30 min and then ceases for the next 90 min. At 120 min the same water application rate is reinitiated for the next 30 min.

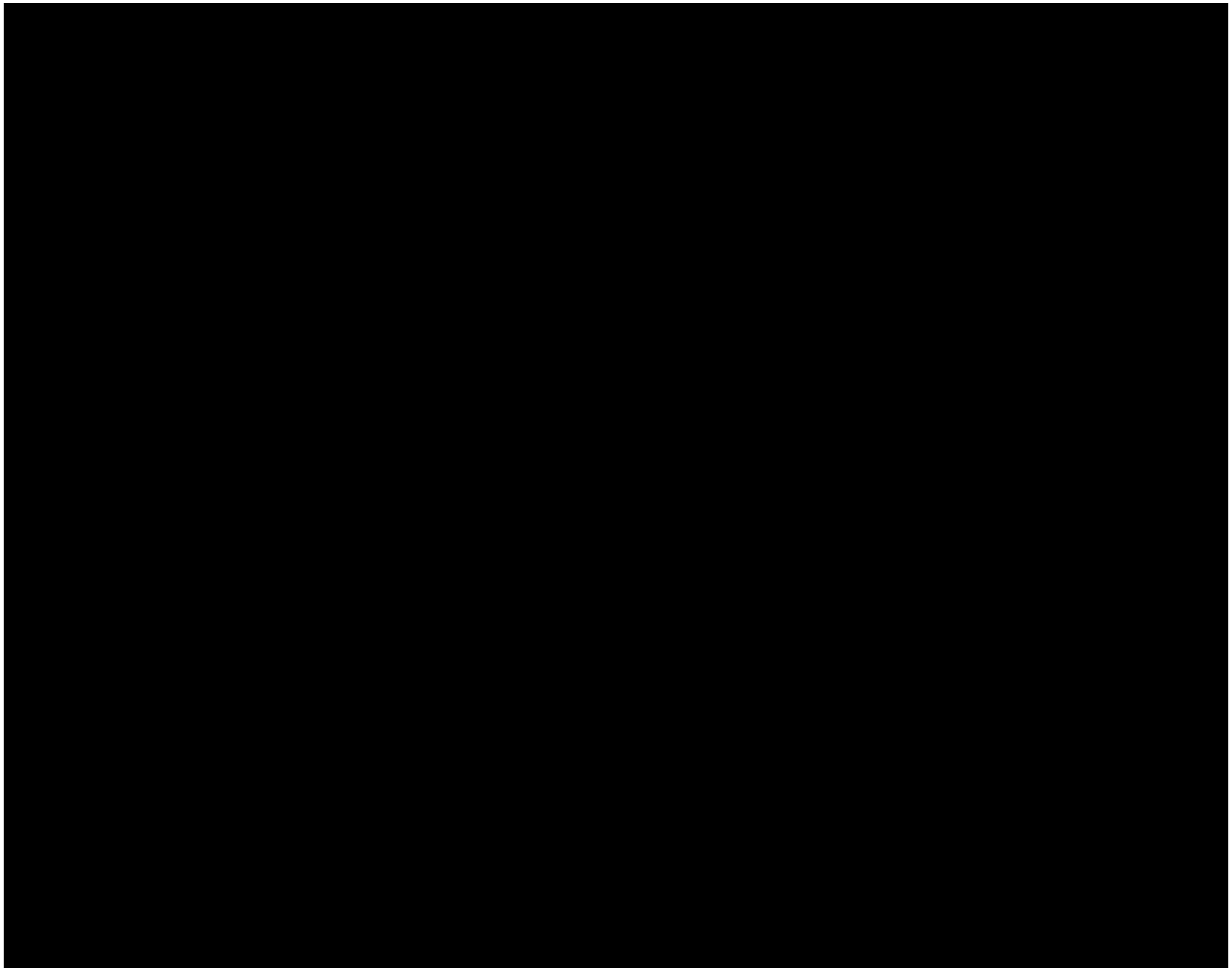

Plate 3. Illustration of diffuse flow in a soil during the first wetting cycle. The flow region and initial conditions are the same as in Plate 2. The main wetting and main drainage branches of the water retention function for the soil are illustrated by the graphic insert.

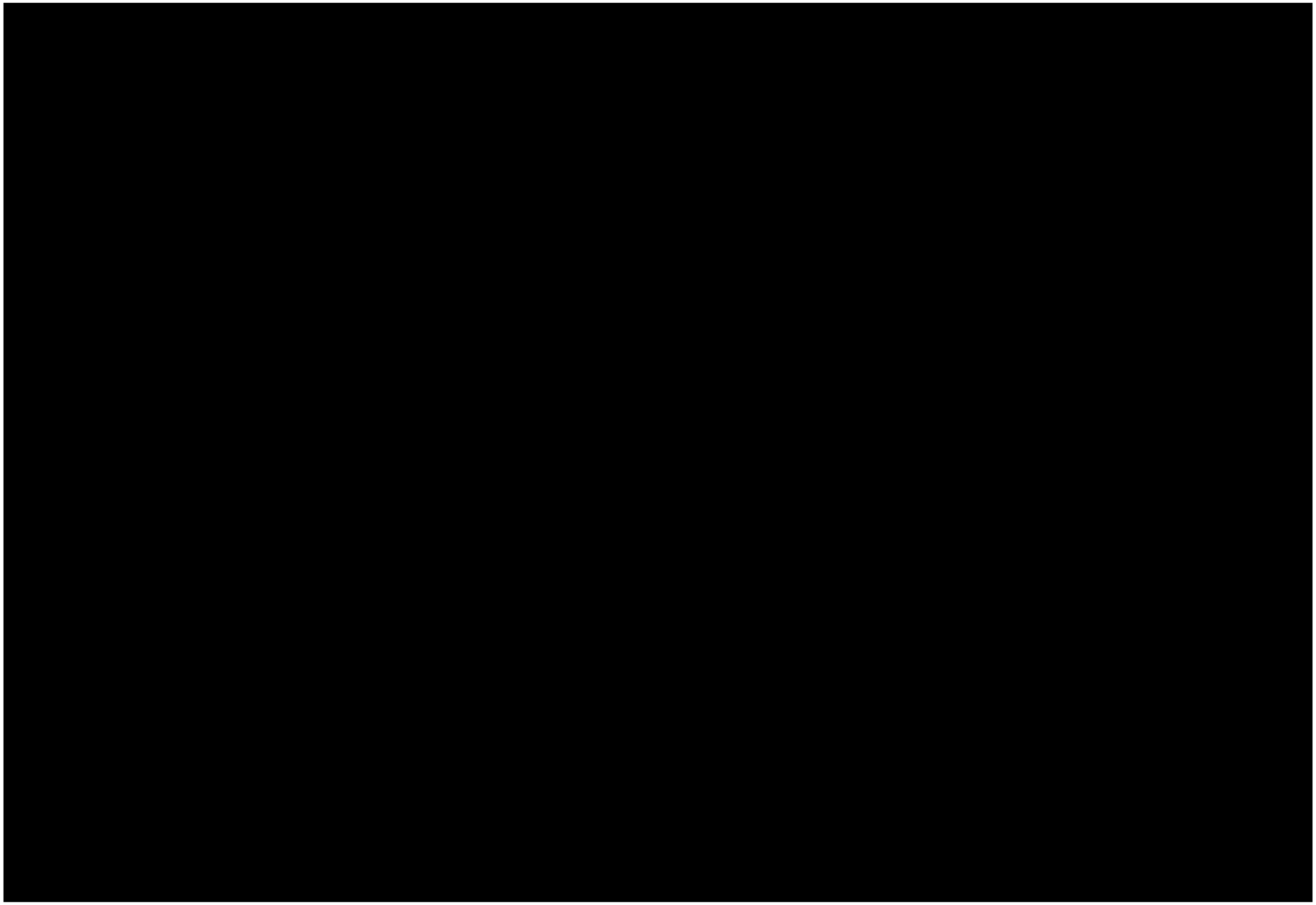

Plate 4. Spatial distribution of volumetric soil water content in the 60-cm-wide, 120-cm-long, 52-cm-deep sand block sampled in Ouddorp. The 8.5% soil water content isosurface and the intersecting (a) horizontal and (b) vertical cutting planes indicate that the vertical fingers started at the layer interface. Volumetric soil water content in the 9-cm-thick humic topsoil ranged from 12% to 40%, while lower contents were found in the sandy subsoil (colored legend indicates water content scale).

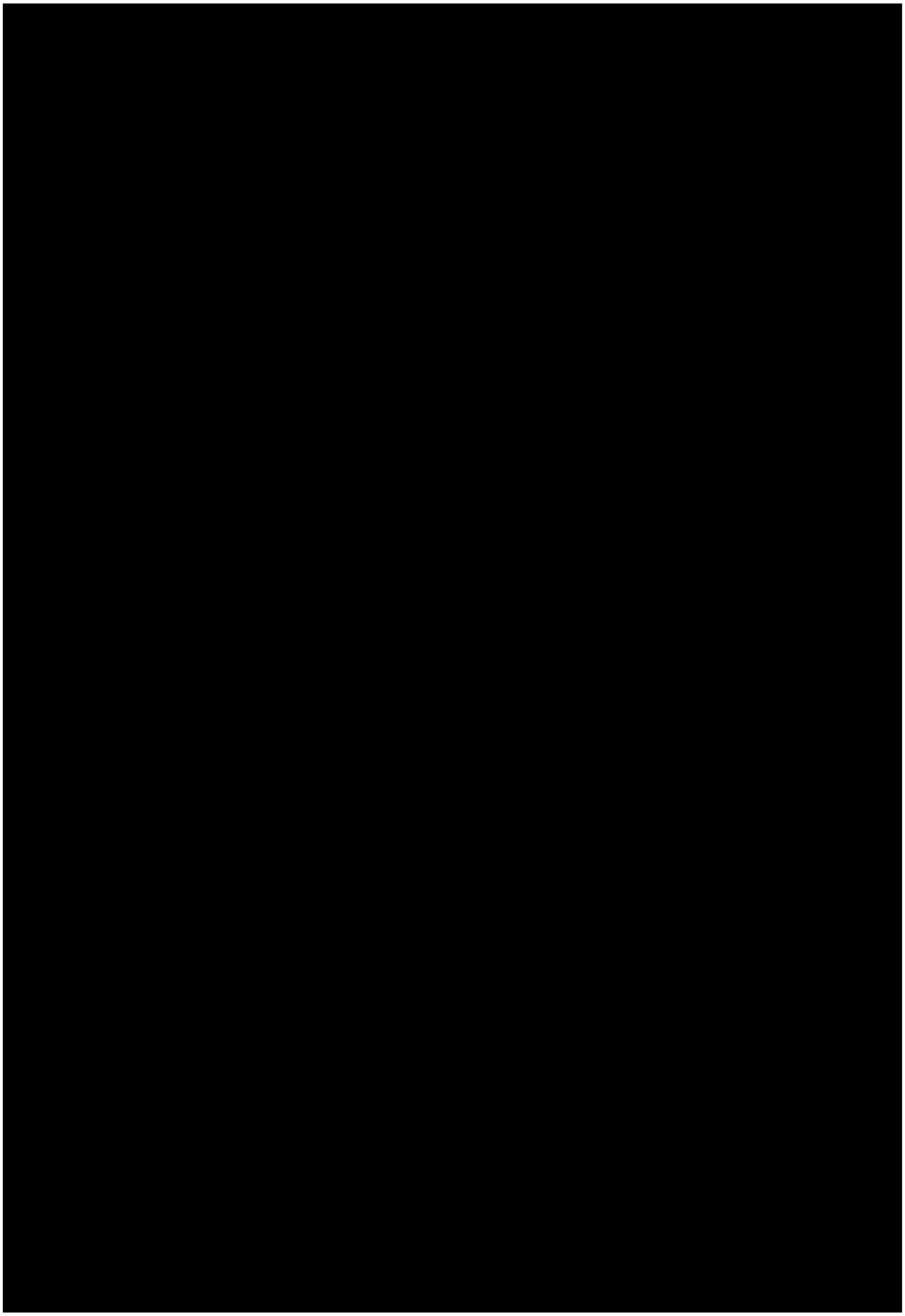

Plate 4. (continued)

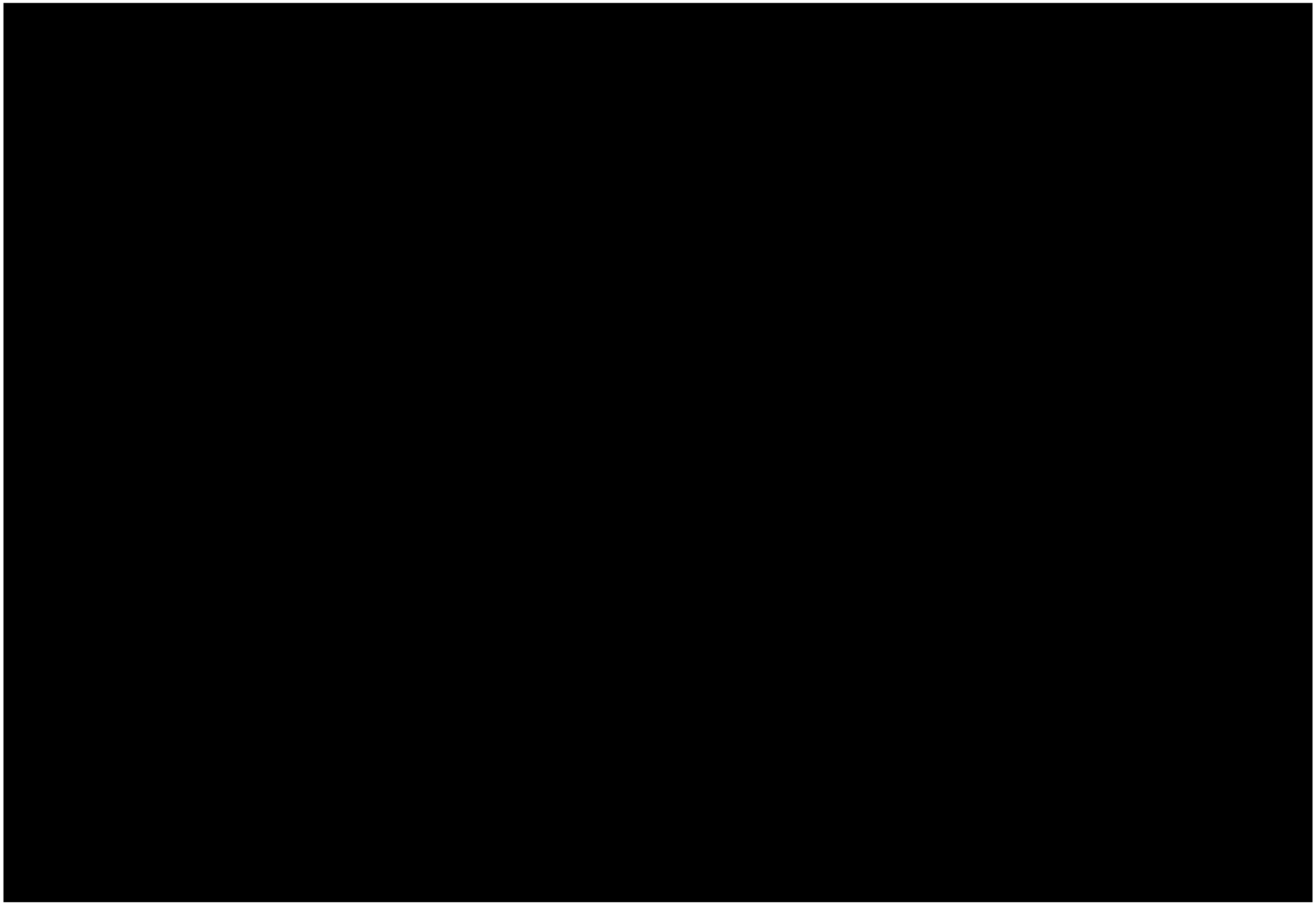

Plate 5. Spatial distribution of potential water repellency classes in the 60-cm-wide, 120-cm-long, 52-cm-deep sand block sampled in Ouddorp showing a water repellent isosurface and intersecting (a) horizontal and (b) vertical cutting planes. Degrees of water repellency are indicated by class values (1, nonrepellent; 10, extremely repellent) in the color legend. Owing to leaching of water repellent substances through the finger, degree of water repellency around the top of the finger shown in the center of Plates 4a and 4b was relatively low and at the finger bottom was relatively high.

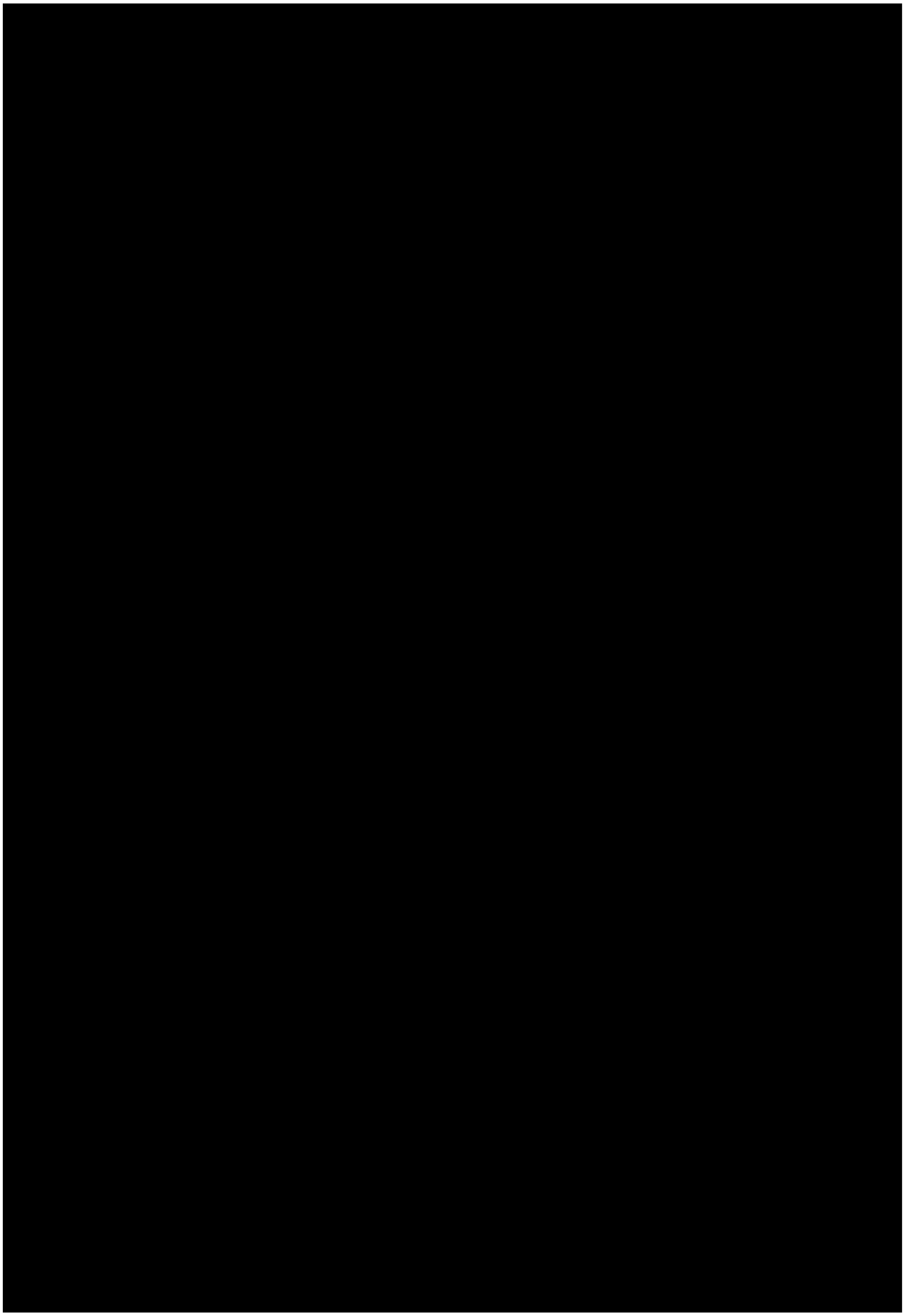

Plate 5. (continued)

and values as low as 1% to 5% in the surrounding soil. Just as in Plate 1, soil water content differences between the fingers and the surrounding dry soil decrease with depth (Plate 4). This can be attributed to the fact that water repellency decreases with depth (Plate 5). It can be seen from the upper horizontal and vertical cutting planes in Plate 5 that water repellency occurs to 40 cm depth, being most extreme at depths of 7–12 cm. Above and below this layer, water repellency is less severe. The origin of the finger in the center of Plate 4 appears to be associated with a "weak" area, with a relatively low degree of water repellency compared to that found elsewhere at depths of 7–12 cm (Plate 5).

Several studies have indicated that infiltrating water may be able to leach organic substances from the topsoil [*Schnitzer and Desjardins*, 1969; *Goh et al*., 1976]. It is hypothesized that the finger in the center of Plate 4 is in the process of becoming a heterogeneity-driven finger. The transport of water repellent substances through the finger causes a decrease in the degree of water repellency around the top of the finger at depths of 7–12 cm and an increase at the bottom of the finger deeper in the profile. This will of course result in different soil water retention curves along the fingered flow pathway and thereby affect the characteristics of unsaturated water flow.

Leaching of water repellent substances through the finger is clearly illustrated by the water repellency distribution shown in the vertical cutting plane in Plate 5, which intersects the entire finger in the center of Plate 4. Relatively low degrees of water repellency were found around the top of the finger, and relatively high degrees were found at the bottom. A similar trend in the degree of water repellency was observed along the finger on the left, although the vertical cutting plane intersecting this finger is not shown in Plate 5.

The relatively low degree of water repellency around the tops of the fingers promotes the occurrence of converging flow into the fingers, while deeper in the profile the relatively low degrees of water repellency in the soil surrounding the bottoms of the fingers cause diverging flow there. The occurrence of converging and diverging flow in the Ouddorp soil has been confirmed by a detailed tracer experiment [*Ritsema et al*., 1993; *Ritsema and Dekker*, 1995]. The leaching of water repellent substances from the topsoil through the fingers is self-progressing, as decreasing water repellency around the top of the finger results in increasing infiltration and vice versa, causing the finger position to become increasingly fixed. This ultimately leads to increasing soil heterogeneity. The measurements shown thus indicate that in the long term, originally instability-driven fingers might become heterogeneity-driven fingers.

6. Discussion

The development of water repellency in soils is a function of time and generally increases in severity with the age of the vegetation [*DeBano*, 1969]. This is why the degree of water repellency is often lower in arable land than in soils with a permanent vegetative cover [*Dekker and Ritsema*, 1996a]. As a consequence, finger positions are probably only fixed in space over long periods of time in those soils with a permanent plant cover. In arable land, where vegetation types are rotated relatively quickly, and where topsoils are often removed and displaced due to tillage practices, finger positions are unlikely to be fixed in space over longer periods of time than the growing season. Therefore the effects of recurring fingers on the process of pedogenesis are expected to be most pronounced in areas with a permanent plant cover.

Mathematical solutions to Richards' equation are inherently stable (in a physical sense) [*Milly*, 1988], but when hysteresis in the water retention function is incorporated, the mathematical solutions may yield unstable flow as a natural outcome [*Nieber*, 1996]. This means that not incorporating hysteresis in a model for water repellent or coarse-textured soils may be seriously misleading, especially for solute transport prediction. Most simulation models are based on some form of Richards' equation and fail to directly address the possible occurrence of unstable flow [*Van Genuchten and Jury*, 1987]. Most field studies, even in sandy soils [*Steenhuis et al*., 1996], have shown that preferential flow is more the rule than the exception, and may partly account for inaccuracies in the prediction of water and solute movement. Since water repellency is plant-induced and occurs often in field soils [*Wallis et al*., 1991; *Wallis and Horne*, 1992], fingered flow may be more common than is presently thought. In our opinion, these models need to be adapted to account for the unstable flow phenomenon if they are to be employed to full benefit.

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